The Advancing State of AF-M315E Technology

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The culmination of twenty years of applied research in hydroxylammonium nitrate (HAN)-based monopropellants, the NASA Space Technology mission Directorate's (STMD) Green Propellant Infusion Mission (GPIM) will achieve the first on-orbit demonstration of an operational AF-M315E green propellant propulsion system by the end of 2015. Following an contextual overview of the completed flight design of the GPIM propellant storage and feed system, results of first operation of a flight-representative heavyweight 20-N engineering model thruster (to be conducted in mid-2014) are presented with performance comparisons to prior lab model (heavyweight) test articles.

The GPIM program will mature green AF-M315E technology to TRL 7+ (with components demonstrated to TRL 9), ready for direct infusion into a broad range of applications. Recognizing, however, that the operating parameters to be demonstrated on GPIM, corresponding to the IHPRPT Phase II goal of +50% greater density-specific impulse than hydrazine represent one design point along a sliding scale, hot-fire results of modified and alternate propellant blends are presented where it is seen that specific performance (Isp or density-Isp) can be directly traded against total deliverable impulse. Specifically, recent tests conducted at Aerojet Rocketdyne have demonstrated AF-M315E to be reactive over a wide range of dilutions with water, whereby reaction temperatures can be reduced to yield substantial gains in thruster life while still retaining significant specific performance advantages over hydrazine, thus broadly extending the range of missions to which GPIM is directly relevant. Additionally presented are test results where GPIM heavyweight hardware was employed to demonstrate the first successful catalytic firing of an enhanced performance propellant formulation delivering +70% greater density-specific impulse compared to hydrazine

I. Nomenclature

EM	=	Engineering model
ESPA	=	EELV secondary payload adapter
GPIM	=	Green Propellant Infusion Mission
HAN	=	Hydroxylammonium nitrate
I_{sp}	=	Specific Impulse
IHPRPT	=	Integrated High Payoff Rocket Propulsion Technology
SCAPE	=	Self-Contained Atmospheric Protection Ensemble
TRL	=	Technology Readiness Level
ρI_{sp}	=	Density-Specific Impulse

II. Introduction

The NASA Space Technology Mission Directorate (STMD) has initiated the Green Propellant Infusion Mission (GPIM) program with the objective of completing the first on-orbit demonstration of a complete high-performance green propellant propulsion system by the end of 2015. Hosted on a Ball Aerospace BCP-100

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ESPA-class spacecraft bus, the GPIM Technology Demonstration Mission (TDM) will employ an Aerojet Rocketdyne-developed advanced green monopropellant payload module as the sole means of on-board propulsion, performing a comprehensive battery of performance characterization and capabilities assessment maneuvers using both 1-N and 20-N class thrusters[1,2,3,4,5] (respectively representing the two largest segments of the monopropellant thruster market). Although current planning calls for the on-orbit segment of the TDM to be completed within three months, the specific intent of the GPIM program is to advance the technology to a readiness level suitable for immediate infusion into a broad range of both short duration and extended missions.

III. AF-M315E Advanced Green Monopropellant

The GPIM demonstration will employ a high-performance green propellant invented at AFRL in 1998 known as AF-M315E, a true ionic liquid derived of hydroxylammonium nitrate (HAN), water, and an also highly hygroscope fuel (vs. other propellant formulations that actually include non-ionic, and in some cases toxic, volatiles such as methanol). Delivering approximately 50% higher ρI_{sp} than hydrazine (5% higher I_{sp} combined with a 46% higher density, AF-M315E offers comparable performance (density-Isp) to traditional storable bipropellants for low ΔV missions while employing roughly half the number of components, thereby retaining the well-established increased reliability and reduced cost of traditional monopropellants. Many design issues and failure modes associated with long-duration interplanetary missions (e.g. control of mixture ratio, of propellant vapor diffusion and reaction, oxidizer flow decay) do not apply to an equally capable AF-M315E system.

AF-M315E (shown as routinely handled in Figure 1) derives its low-toxicity-hazard characteristics and high mixture stability (even to very low temperatures) from the high solubility and negligible vapor pressure of all solution constituents, such that indefinite exposure to the open environment poses no safety issue. As such, AF-M315E simplifies the safe design and development of propulsion systems compared to conventional toxic propellants such as hydrazine. Since leakage of AF-M315E has been verified as a critical rather than catastrophic failure with range safety personnel per AFSPCMAN 91-710, only single-fault-tolerance is required for safety in handling flight systems. This alone accounts for significant savings, as redundant components are eliminated, yielding simpler architectures. Further, simpler and much less expensive design and verification criteria govern flight-qualification of fracture-critical hardware (e.g., propellant tanks) for non-hazardous propellants such as AF-M315E compared to hydrazine. The aggregate potential impact of these and increased performance-related cost savings is highly mission-dependent, but has been evaluated to tens of millions of dollars for large space missions such as JUNO, MSL, and Europa; and to several million for more modest missions such as GRAIL and MRO[6].

With its ultra-low minimum storage temperature, AF-M315E yields an additional advantage mitigating operational concerns related to long-duration system thermal management. Whereas hydrazine space tanks and lines must be heated at all times to prevent freezing, AF-M315E cannot freeze (it undergoes glass transition at -80 ºC). Thus, during long coast periods an AF-M315E propulsion system may be allowed to fall to very low temperatures and later reheated for operation without risk of line rupture by phase-change-induced expansion. This can be

Figure 1 AF-M315E propellant can be safely handled in open containers without need of respiratory protective equipment

particularly beneficial with respect to the often limited power budgets of smallsats, as well as interplanetary spacecraft and planetary ascent vehicles, which missions can call for years of propellant storage in cold environments. For <1 AU interplanetary exploration missions, solar power is naturally more limited than for Earth-orbiting satellites; e.g., equivalent solar power generation designs in Mars (e.g., MRO), Vesta (e.g., Dawn), and Jupiter (e.g., JUNO) orbits produce roughly 43%, 16%, and 3.7% of the electrical power they yield in Earth orbit, respectively. Tests also have demonstrated AF-M315E to have a significantly reduced sensitivity to adiabatic compression than hydrazine and other green propellants.

The cost savings of green propellants associated with simplified range operations are quantifiable. The average contractual cost to load a NASA mission with conventional propellants is $135,000[6]. The cost for loading with AF-M315E will be a small fraction of this, and the associated schedule significantly expedited. Per current conventions, propellant loading operations require one shift for setup in SCAPE, a second shift waiting for propellant test confirmations, a third shift or more for actual loading, and a final additional shift to break down the setup, during which all remaining launch processing staff must wait at costs exceeding $100k/day for a typical Class B NASA mission. Thus elimination of the interruption of launch processing associated toxic propellant loading can save more than $100k per launch and two shifts of schedule. Naturally, it follows that simplified range operations would equally benefit commercial users through lower launch costs. An early Aerojet Rocketdyne study evaluating replacement of hydrazine with a HAN-based advanced monopropellant for Centaur RCS on an Atlas launch vehicle concluded ground support costs of fueling could be reduced by two-thirds[7].

IV. GPIM Propulsion System Overview

Under development as a self-contained module to allow independent assembly at Aerojet Rocketdyne for high-level integration with the BCP-100 bus, the GPIM demonstration payload configuration, illustrated in Figure 3 and shown in schematic in Figure 2, bears high similarity to a traditional hydrazine system. Designed to intiegrate with the host spacecraft via its standard payload interface plate (PIP), the GPIM demonstration payload comprises a simple, single-string, blow-down AF-M315E advanced green monopropellant propulsion system employing a single Aerojet Rocketdyne GR-22 (20-N class) primary divert thruster centered on an upper deck topping the payload's box-like primary structure and surrounded by four GR-1 (1-N class) attitude-control thrusters mounted one each at the adjacent corners. Because the AF-M315E propellant exhibits good compatibility with standard 6Al-4V titanium, propellant feed system components were able to be selected from a subset of heritage hydrazine system components that are compatible with little or no modification. (AF-M315E is not compatible with iron-bearing metals for long duration storage.) Likewise, the propellant tank, housed within the primary structure and aligned with the primary thrust axis is a conventional ATK model 80581 hydrazine propellant tank, the materials of construction of which have already been successfully verified in thermally accelerated aging tests to be compatible with AF-M315E for

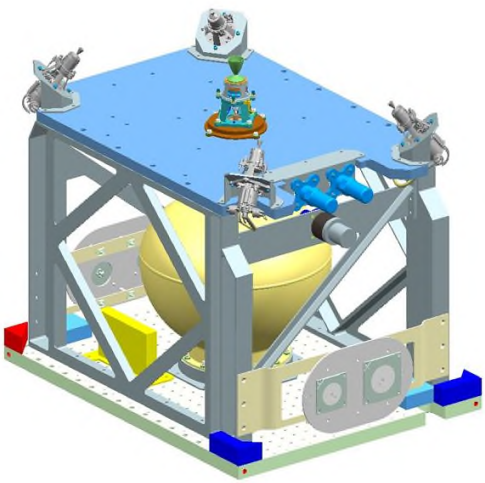

Figure 3 AF-M315E Propulsion System

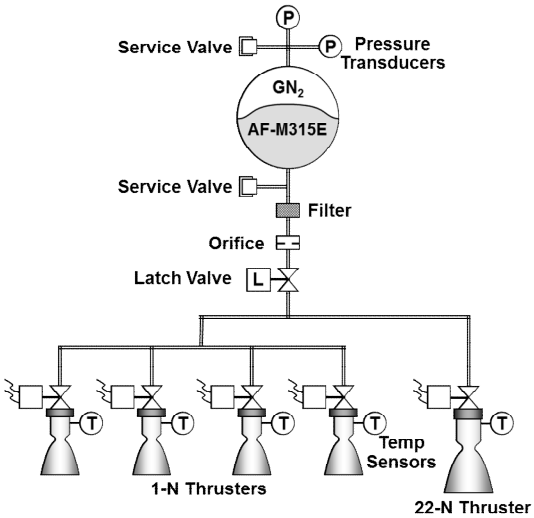

Figure 2 Propulsion System Schematic

durations of up to at least two years.

Aside from the 50% increased impulse delivered at comparable system volume, mission design-related distinctions between the GPIM and a traditional hydrazine system relate principally to differences in the thermal characteristics of AF-M315E vs. conventional thrusters. Due to the advanced monopropellant thrusters' elevated minimum start temperature, catalyst bed preheat power requirements are higher compared to a conventional hydrazine system. This increase is partially offset, however, by savings associated with the thrusters' single (instead of conventional dual) seat valves (see below), as well as much reduced required power for system thermal management during non-operating periods facilitated by the propellant's demonstrated storability at very low temperatures. Radiation and conduction from the advanced monopropellant thrusters' high temperature chambers also impart a moderate increase in the thermal load to the system mounting interface.

V. GPIM Green Advanced Monopropellant Thrusters

Representing the culmination of over two decades of research and development, Aerojet's GR-1 and GR-22 advanced monopropellant thrusters (Figure 4) combine a breakthrough high temperature catalyst with stability-enhancing design techniques to enable duty-cycle-unlimited operation on state-of-the-art green ionic liquid propellants while delivering substantially improved performance and reduced handling costs compared to conventional toxic monopropellants. Though bearing general resemblance to the series-assembled valve, injector, catalyst chamber, and nozzle of standard catalytic hydrazine thrusters of similar thrust class, the common core architecture of both designs incorporates a number of optimizations specific to the increased thermal management requirements of high-performance (and higher flame temperature) advanced monopropellants. Most immediately distinctive are the thrusters' two-piece extended stand-off structures. Serving to minimize heat soak-back to the mounting interface during and following extended thruster firings, this innovative design approach confines the need for high-temperature refractory alloys to the thrust chambers and nozzles, allowing a significant portion of both thrusters to be fabricated from lower cost-conventional nickel alloys. In supporting the thrust chamber from the downstream end, this increased thermal isolation is accomplished with no added length in either case, while heat dissipation during catalyst bed preheating to the nominal 315 ºC start temperature, and thereby associated power, are minimized.

In accordance with engineering best practices, both thruster designs incorporate redundancy on all fracture-critical structural elements, including both portions of the mounting structures and all bolted joints/interfaces. Engineered to the same composite dynamic load specifications developed by Aerojet Rocketdyne to ensure broad mission utility for state-of-the-art hydrazine thrusters, the GR-1 and GR-22 are readily infusible into a wide range of applications where conventional monopropellants currently dominate.

Both thrusters also employ notably smaller, single-seat valves with higher net reliability than the two-seat scheme generally favored for comparable hydrazine thrusters. This results from an inadvertent benefit inherent to specific properties of ionic liquid propellants. Being typically more viscous than hydrazine, ionic liquid propellants are intrinsically far less prone to leakage, such that the added cost and doubled risk of a thruster becoming inoperable in the event of either of two redundant stages failing closed is not justified. Moreover, having essentially

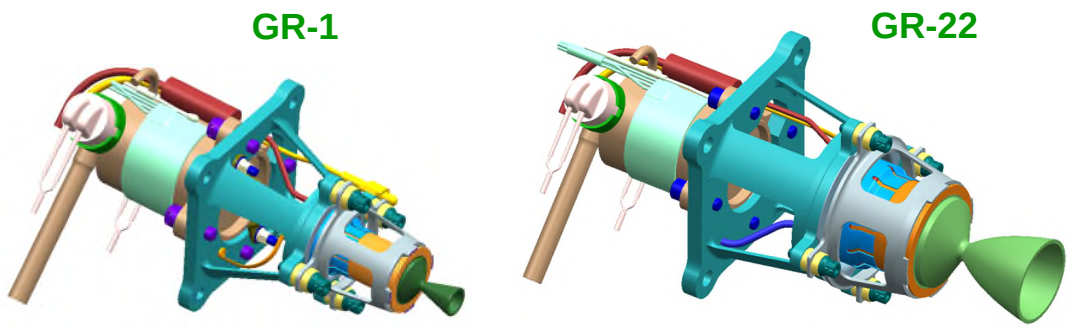

Figure 4 Aerojet GR-1 and GR-22 Thrusters

no vapor pressure, true ionic liquids will not self-pressurize or evaporate through small fissures such as a flaw in a valve seat. In the very unlikely event that thruster valve leakage should occur, isolation of the downstream feed system by closing an upstream system latch valve will fully prevent any loss of propellant. Likewise for launch range operations, the innate safety of ionic liquid propellants, accounting for both their low vapor toxicity and inability to activate un-preheated thrusters or react with external system and immediate work environment materials (unlike hydrazine), obviates conventional rationale for the use of dual-seat thruster valves. Thus, single seat valves provide higher mission assurance at lower mass, power (partially offsetting added preheat power requirements), and cost. Further, the resulting compactness of the GR-1 and GR-22 designs facilitates integration within the close packaging of small spacecraft where the high density-Isp offered by ionic liquid propellants is most advantageous. Single seat valves have actually been used on many hydrazine-propelled spacecraft, and particularly NASA missions such as Cassini, Deep Impact, New Horizons, and Voyager (still successfully operating since its launch in 1977). Note, however, that unlike these examples, range safety has not required the addition of a secondary upstream latch valve to compensate for the loss of redundant leak inhibits on the thrusters for the GPIM demonstration, owed the inherent safety characteristics of the propellant.

The ongoing GPIM flight thruster development effort is structured in three overlapping phases. Results of sea-level testing of heavyweight hardware completed in Phase 1, principally focused on, and derived from parallel preliminary design activities associated with, the less mature (at the program outset) 20-N class thruster, are discussed in the next section. Now nearing completion, Phase 2 comprises first fabrication and (hot-fire and environmental) protoqualification testing of flight-weight engineering model thrusters (see Figure 5). In Phase 3, flight designs will be finalized and flight and qualification units fabricated. All thrusters will undergo standardized acceptance testing, comprising protoqualification shock and vibration testing as well as a check-out hot-fire. Qualification units will thereafter be subjected to qualification-level shock and vibration loads, followed by a mission-representative life test. On orbit, the thrusters will perform a series of maneuvers designed to both fully characterize thrust, impulse bit repeatability, specific impulse, and thermal performance over a variety of duty cycles intended to encompass the full needs of near-future space applications.

Figure 5 GPIM engineering model hot-fire testing will commence with the GR-1 thruster in early June, 2014

VI. Heavyweight 20-N Class Thruster Development and Testing

At the outset of the GPIM program the baseline GR-22 design comprised the hybridization of an extensive body of heritage thruster development efforts spanning 0.4-650 N thrust and more than ten years with key, more recent, thruster design and materials advancements that had only been demonstrated at the 1-N level. In preparation for the program, extensive thrust-density scale-up testing was performed using subscale hardware, such that the resulting

conceptual GR-22 design comprised essentially a 3× scaling by simple parallel combination of three instances of an already-tested design operating within established performance parameters (e.g. chamber pressure, catalyst bed loading, injector loading, etc.). Nevertheless, initial testing of a heavyweight test article demonstrated slow washout (loss of complete combustion) for all duty cycles over 20% at nominal maximum thrust, along with moderate start-up chamber pressure spiking, indicating a critical flaw in the scale-up approach and grasp of the underlying governing mechanics.

A thorough comparative analysis of subscale and full scale design and performance data was undertaken, ultimately identifying a previously unrecognized flame-front instability associated with the phase-boundary-coupled reaction mechanics unique to the ionic liquid propellant, shedding light not only the unexpected results encountered on the present development effort, but also occasional previous test anomalies dating years back that had remained unexplained. In response to these findings, a series of candidate design revisions designed to mitigate the instability were developed and implemented as retrofits to the modular 22-N heavyweight test thruster in six configurational combinations for hot-fire test. As illustrated in Figure 6, the relative performance of each configuration was compared according to the maximum achievable thrust. Whereas all cases showed improvement over the baseline, a high degree of sensitivity was observed to relatively small geometric differences, with the combined features down-selected for the final configuration both individually and as tested in combination showing substantial advantages over their alternatives. Before conclusion of the test effort, the down-selected configuration had successfully demonstrated stable operation over a comprehensive range of duty cycles and sufficient thrust density to support a final flight design capable delivering just over 20 N at maximum beginning-of-life system operating pressure for the GPIM flight demonstration. No washout was observed when throttled in margin testing up to a thrust level of 27.5 N. While determination of maximum thruster life was not a specific test objective (as upcoming flight-weight engineering model testing will provide a higher fidelity assessment), the 10 kg total throughput achieved without any observed performance degradation or significant change in chamber pressure roughness represents a substantial margin over the requirements for the GPIM on-orbit demonstration mission.

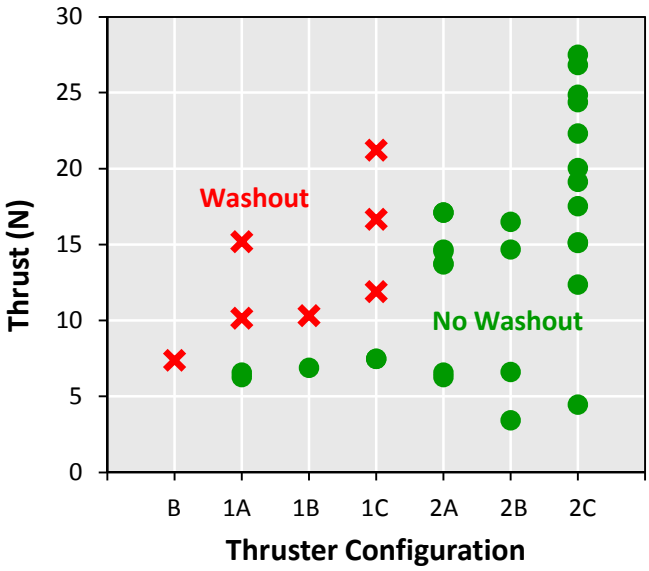

Figure 6 Maximum achieved thrust vs. thruster configuration

VII. Post-Heavyweight-Test-Program Predicted Flight Thruster Performance

Designed as functional alternatives to Aerojet Rocketdyne's 1-N class MR-103G and 22-N class MR-106L, thrust vs. feed pressure characteristics for the GR-1 and GR-22 are presented in Figure 7, with key operating metrics summarized in Table 1. Operational testing of the first flight-weight engineering units is scheduled to begin in late April 2014.

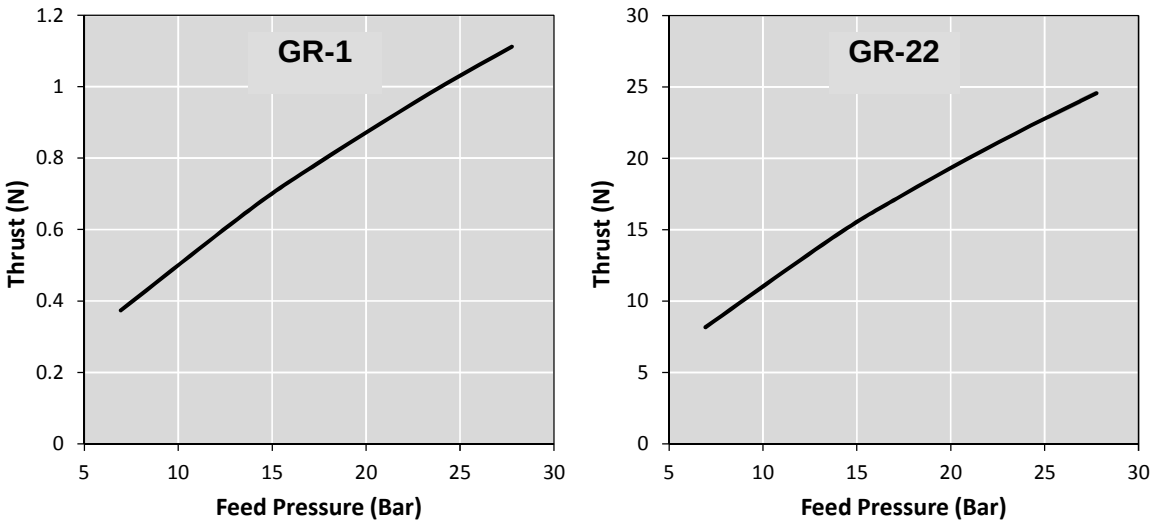

Figure 7 Aerojet Rocketdyne GR-1 and GR-22 Thrust vs. Feed Pressure Curves

Table 1 Thruster Predicted Performance Summary

	GR-1	GR-22
Thrust (N)	0.4 - 1.1	6 - 22
Feed Pressure (bar)	7 - 32	7 - 32
Nozzle Expansion Ratio	100:1	100:1
Valve Power (W)	9	16
Preheat Power (W)	14	35
Specific Impulse (s)	235	250
Density-Specific Impulse (g-s/m3)	345	368
Total Impulse (N-s)	23,000	74,000
Minimum Impulse Bit (mN-s)	8	116

VIII. Aerojet Rocketdyne's Advanced Propellants Test Lab

In support of the GPIM program, Aerojet Rocketdyne has established the Advanced Propellants Test Lab as a significant expansion of its as Redmond, Washington, USA-based advanced propellant development and testing capabililities. To date, the facility houses a single state-of-the-art 1.8 m dia × 2.6 m long cylindrical stainless steel high-altitude cell (left in Figure 9). Equipped with a 64-channel Dewetron 204 kS/s data acquisition system and dual Stokes 1739 combination vacuum pumps supporting testing down to 2.7 mbar, the test ensemble provides capacity well exceeding GPIM program requirements in preparation for future development and production needs. Further, the test cell has been designed and installed with provisions for the retrofit of a diffuser/ejector to enable high-altitude testing of thrusters up to 1 kN. Correspondingly, the built-in propellant management system (right in the figure) employs 19-mm (0.75-inch) primary feed lines. Two thrust stands are available, currently outfitted for testing of the GPIM 1-N and 20-N class thrusters.

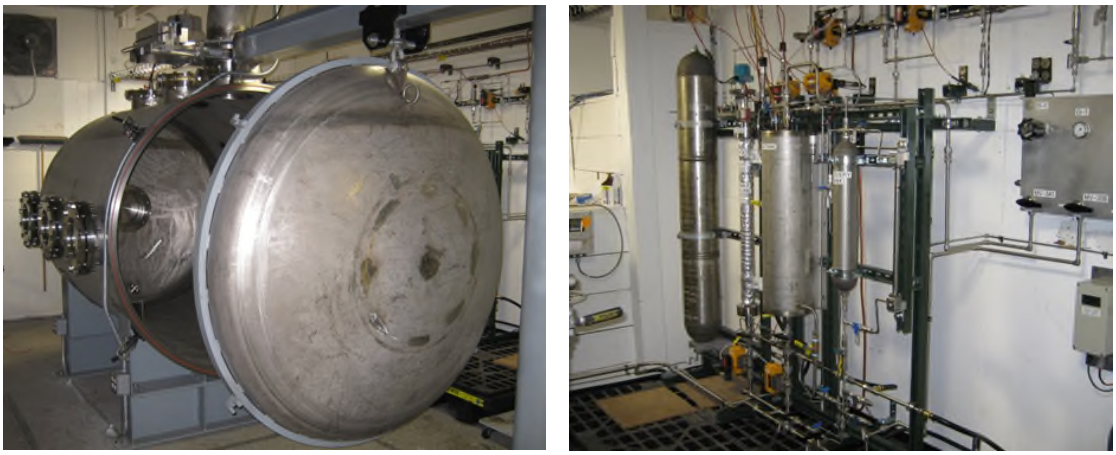

Figure 9 Aerojet Rocketdyne's now operational Advanced Propellants Test Lab stands ready to begin GPIM flight-weight engineering test units in late April.

IX. Looking Beyond the GPIM Demonstration [*Content in red text to be reviewed by AFRL*]

While the GR-1 and GR-22 thrusters have been designed to withstand the high thermal requirements of AF-M315E propellant, operation of (heavyweight) thrusters has been demonstrated over a broad range of propellant dilutions with water (up to 40%) with no significant impact to required preheat temperature and power. Moreover, currently available data corroborates expectations that dilutions corresponding to relatively small reductions in performance yield substantive extensions in thruster life. Thus, for any given mission a balance may be struck between specific impulse and maximum total impulse that may be delivered by a single thruster. Additionally, as propellant tailoring involves only the addition of water, existing sensitivity and compatibility data (and related certifications) remain valid as bounding limits. To quantitatively assess these potential benefits, Aerojet Rocketdyne recently completed a thruster life test identical in all respects to a previous life test of a heavyweight version of the GR-1, but with 10 vol% water added to the propellant. As illustrated by the data presented in Figure 8 alongside a notionally sketched total delivered impulse vs. ρIsp curve, whereas this reduced performance blend delivers approximately 37% increased ρIsp and equivalent Isp to hydrazine (as compared to AF-M315E's +50% ρIsp and +9% Isp), a 20% increase in total impulse life capability of the thruster was achieved. (The curvature shown in the

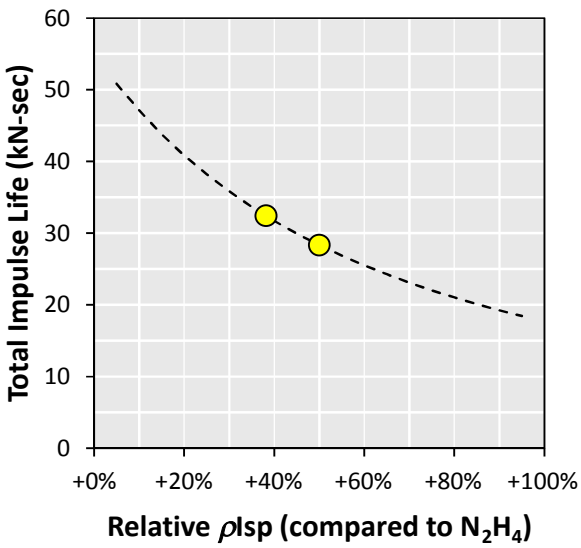

Figure 8 1-N thruster demonstrated life capability vs. specific performance

projection derives from assumed vertical and horizontal asymptotes in the limits where ρIsp approaches zero and very high values.) Anticipating this result, and a class of potential near-term adopters desiring substantially better than hydrazine level performance but more total impulse than is currently achievable using full-strength AF-315E propellant, the ready ability to substitute coated C-103 alloy for the baseline rhenium chamber material of construction has been incorporated as a cost-reducing option into the design of both the GR-1 and GR-22 thrusters.

The flexibility of the GPIM thrusters to accept a variety of different propellants was further demonstrated through the employment of the 1-N heavyweight test hardware to perform first hot-fire assessments of two alternative ionic liquid blends. Principal test objectives for the two experimental formulations were to assess operational stability and parametrically determine minimum required catalyst bed preheat temperatures. The first propellant, a slightly lower (than AF-M315E) performing blend, operated stably at catalyst bed preheat temperatures of 371 ºC (700 ºF) and above, but did not achieve its formulation objective to improve low temperature catalytic response, demonstrating catalyst bed fouling and washout at the next lower tested preheat temperature of 316 ºC (600 ºF) as illustrated by the chamber pressure transients shown in Figure 10A. (The same thruster has been verified to perform similar full-thrust starts to steady-state operation from 288 ºC (550 ºF) when operating on AF-M315E.) While the higher-performance second tested formulation exhibited partial washout following a moderate chamber overpressure transient when started from below a similar minimum preheat temperature (Figure 10B), its demonstration of stable operation from higher preheat temperatures represents a significant milestone as the first successful operation of a catalytic thruster on propellant delivering a 70% ρIsp increase over hydrazine. Although the 100 g available propellant sample limited testing to very short duration, that disassembly and inspection of the test article showed no detectible attrition of the catalyst or other thruster internals by the new propellant's approximately 2300 ºC reaction products indicates sufficient life capability for at least tactical, and potentially small satellite, mission needs.

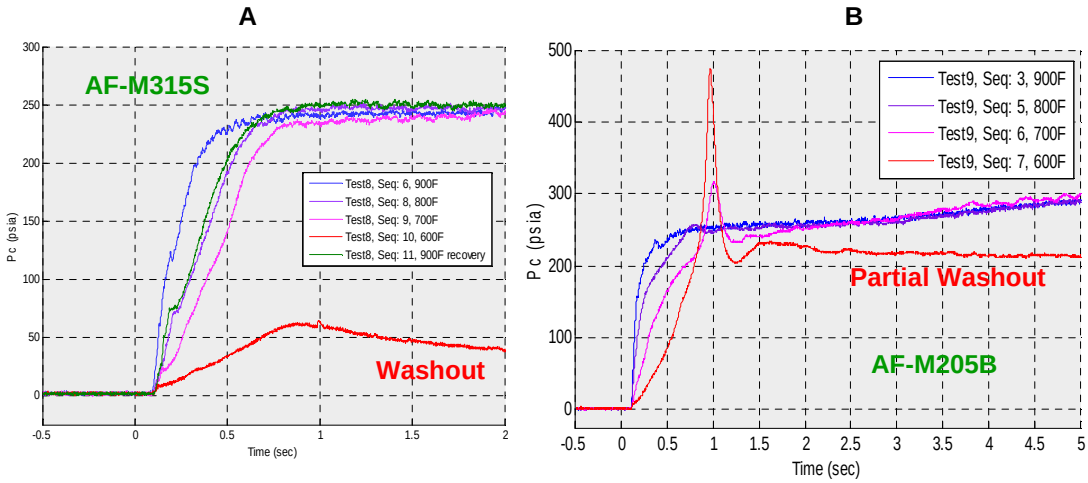

Figure 10 1-N thruster chamber pressure ignition transients operating on experimental alternative propellants

X. Conclusion

The combined mission-enabling high performance, cost-reducing inherent safety, and approaching technical maturity of AF-M315E technologies promise significant near-term benefits to space and defense community users of conventional propellants. Now approaching the end of the second of three development phases to culminate with the first on-orbit demonstration of a green propulsion system delivering 50% greater ρIsp than hydrazine by the end of 2015, the GPIM program is on track to sufficiently mature AF-M315E propulsion system technology (to TRL 7+) for ready infusion into a wide range of applications. As an early benefit, early development activities undertaken in support of GPIM have already yielded important breakthroughs relevant to the scaling of thrusters well above the thrust classes to be employed in the program's objective on-orbit demonstration. Moreover, recent test efforts employing modified and alternate propellant formulations portend expanded capabilities for the technologies being matured under GPIM, demonstrating the ability to tailor an optimum balance of specific performance and total

impose for specific mission needs, as well as the first successful operation of a catalytic thruster on a propellant delivering +70% increased ρIsp compared to hydrazine. GPIM flight-weight engineering test articles are near completion with testing scheduled to begin in Aerojet Rockedyne's new Advanced Propellants Test Lab starting mid May 2014.

XI. Acknowledgments

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